Monitoring Air-Sea Exchange Processes Using the High Frequency Ambient Sound Field

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LONG-TERM GOAL

The ambient sound field contains information about the processes generating the sound and the intervening media modifying the sound. This research seeks to demonstrate measurement of useful ocean surface processes using passive measurements of the high frequency underwater ambient sound field. This will allow passive monitoring of environmental conditions from simple and robust sensors, namely hydrophones. In turn, given environmental weather conditions, predictive Naval ocean ambient noise models will be improved. This technique introduces no acoustic disturbance to the environment, and is hence covert and poses no potential harm to marine mammals or other forms of life in the ocean.

The frequency range of interest is from 200 Hz to 50 kHz. In this frequency range, the dominant natural sources of sound are breaking wind waves and precipitation. The sound generated by these phenomena can be subsequently modified through attenuation by ambient bubbles. These features of the air-sea interface: breaking waves, precipitation and bubbles, are an important part of the exchange of momentum, heat, water and gas between the ocean and the atmosphere. Coupled air-sea models are currently the weakest of the numerical models needed to analyze and forecast environmental (weather) conditions. Modelers have identified the need for data, especially of wind and rain, to develop and verify these models. Acoustical inversion of the sound field should be able to provide these data, even in remote and difficult regions where more conventional measurements are unavailable.

SCIENTIFIC OBJECTIVES

Inversion of the underwater ambient sound field consists of two general components: identifying the source of the sound, and then quantifying it. Nystuen and Selsor (1997) showed the identification of four ocean surface conditions producing distinctive features in the sound spectrum. These are wind, drizzle, heavy rain and ambient bubbles present (Fig. 1). Once classification is obtained, there are several algorithms available to quantify wind speed (Vagle et al., 1990) and precipitation (Nystuen et al. 1993; 1996; 2001). These algorithms are being evaluated under different environmental conditions to determine if modifications are needed. One of the more exciting new directions of this research is the quantitative estimation of ambient bubble populations. Conditions generating detectable ambient bubbles include high winds alone (Farmer and Lemon, 1984), very heavy rainfall (Fig. 1) and rain in the presence of high wind. These passive acoustic void fraction estimates need to be documented. The

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14. ABSTRACT
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presence of these bubbles suggest that periods of enhanced gas exchange can be detected using passive acoustics.

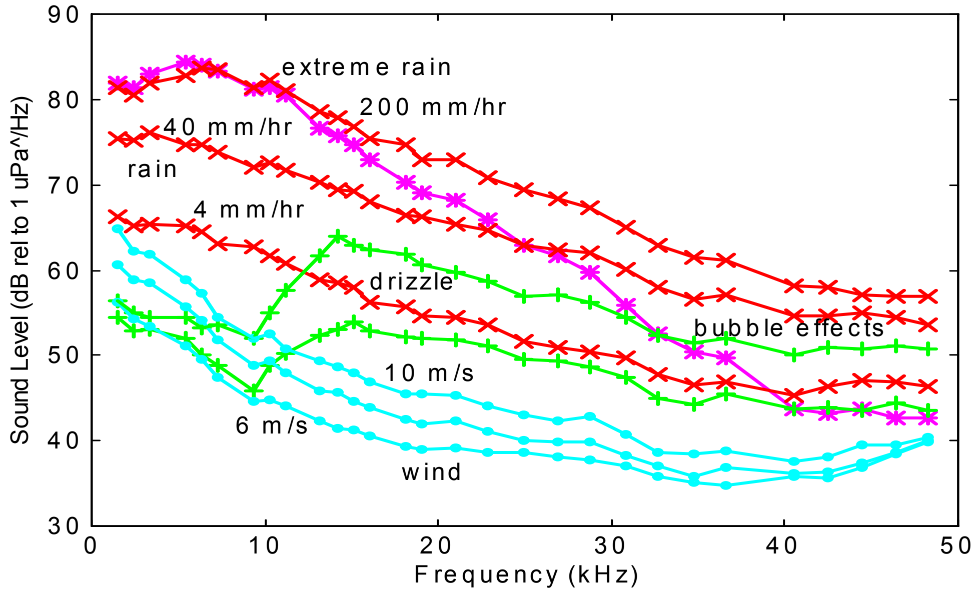

Figure 1. Examples of oceanic sound spectra for wind, rain, drizzle and extreme rain (200 mm/hr) from the South China Sea. One of the spectra for extreme rain shows depressed high frequency (over 20 kHz) sound levels due to absorption by a sub-surface ambient bubble layer. It was recorded five minutes after the other extreme rain spectrum. This indicates that extreme rain is injecting bubbles into the ocean surface.

TECHNICAL APPROACH

Multiple ocean ambient sound data sets have been obtained and the collection of new data sets is ongoing. Archived data sets include: OASIS (North Sea at 2000 m, Zedel et al. 1999), ASREX (North Atlantic, mid-winter), SCSMEX (South China Sea monsoon season, Lau, 1998), ANS Drifters (various locations worldwide) and MARS (Miami sheltered pond, rainfall). New data sets are being collected using Acoustic Rain Gauges (ARGs), designed and built at the Applied Physics Laboratory. ARGs are currently deployed on deep ocean moorings in the tropical Pacific Ocean warm pool region, the eastern Pacific ITZC and the stratus deck region near Peru. Over 80 buoy months of data have been collected. ARGs have also been deployed in Crater Lake, Oregon (a deep freshwater lake) and in a coastal, shallow water location off the west coast of Florida. These data sets include various ancillary information, which will be used to interpret the sound field and show the influence of rainfall on ocean structure. A particular focus will be placed on rainfall detection, classification and quantification as the need for oceanic precipitation data is critical for many scientific studies of the structure and dynamics of the upper ocean.

WORK COMPLETED

The MARS rainfall data set has been analyzed to document the potential and the limitations of the acoustical inversion to quantitatively measure raindrop size distribution within rain (Nystuen, 1999;

2001). The drifter data set has been analyzed to validate acoustic wind speed measurements and rainfall detection by comparison to passive microwave satellite data (Nystuen, 1997). The ASREX data set has been analyzed to produce a climatic-type rainfall record for the duration of the experiment and to provide rainfall rate data for process studies on the influence of rain on other air-sea exchange processes. The ASREX data also demonstrate the potential of using the ambient sound field to quantitatively estimate ambient bubble populations in the near-surface layer of the ocean. Three generations of acoustic rain gauges (ARGs) have been designed, built and deployed in a variety of oceanic situations. Data from the South China Sea Monsoon Experiment (SCSMEX) demonstrate acoustic detection of rainfall and the potential to classify rainfall type (Nystuen et al., 2000). Vandalism is a serious problem for surface instrumentation at sea. On several deployments, ARGs mounted underwater on the mooring line were undetected by vandals and were the only instruments to continue to provide data for the experiment after the attacks. The new generation ARGs are performing well and providing new data sets on a regular basis from various deployment situations.

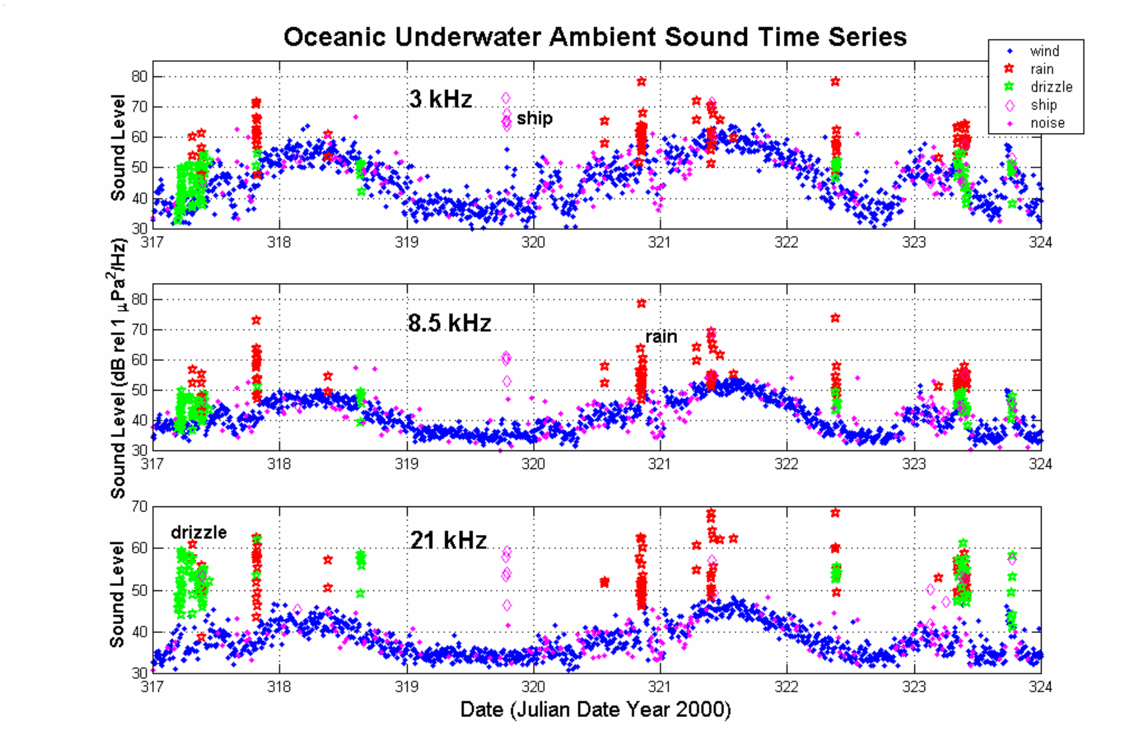

Figure 2. This figure shows time series of oceanic underwater sound at 3 different frequencies (3, 8.5 and 21 kHz) recorded from an Acoustical Rain Gauge (ARG) mounted on a deep ocean mooring at 40 meters depth. The mooring is part of the NOAA TAO array and is located at 10ºN, 95ºW. The different sources of sound are identified by comparing spectral intensity levels, spectral shapes and temporal variances of sound intensities.

RESULTS

The first step in the analysis of oceanic ambient sound data is to identify the present surface weather conditions (wind, drizzle, heavy rain, ambient bubbles present) (Nystuen and Selsor, 1997). Figure 2 shows an example of the time series of the underwater sound levels at three different frequencies from an

ARG mounted at 40 m depth on a deep ocean mooring at 10ºN, 95ºW. The sound sources are identified based on the spectral and temporal characteristics expected from rain, drizzle, wind and other noises such as ships. The geophysical interpretation of the acoustic data is shown in Figure 3 and compared with co-located mooring-mounted R.M. Young anemometer and rain gauge. The quantification of wind speed is excellent (± 0.4 m/s), at least for wind speeds over 3 m/s. The acoustic wind speed measurement depends on the sound generated by breaking wind waves. For wind speeds below 3 m/s there is no acoustic signal as wave breaking is minimal. The co-detection of precipitation events is also excellent.

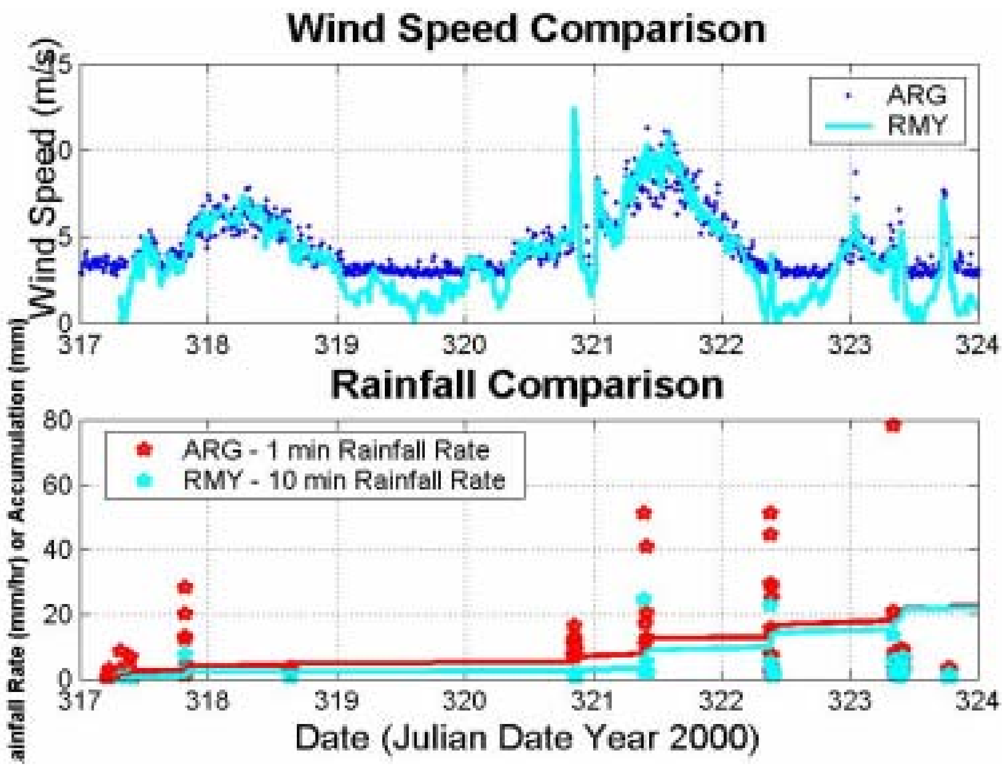

Figure 3. This figure shows the acoustic interpretation of the time series shown in Fig. 2. The acoustic wind speed measurement agrees with the RMY anemometer to ± 0.4 m/s for wind speeds greater than 3 m/s. The acoustic wind speed algorithm (Vagle et al. 1990) has a mathematical minimum of about 3 m/s. Co-detection of rain events from the ARG and RMY rain sensors is excellent. The ARG measures instantaneous rainfall rate, while the RMY rain gauge must be averaged over a finite time interval. In this case, 10 minutes is used to reduce instrumental error (Serra et al., 2000). Direct comparison between the instruments can be achieved using rainfall accumulation.

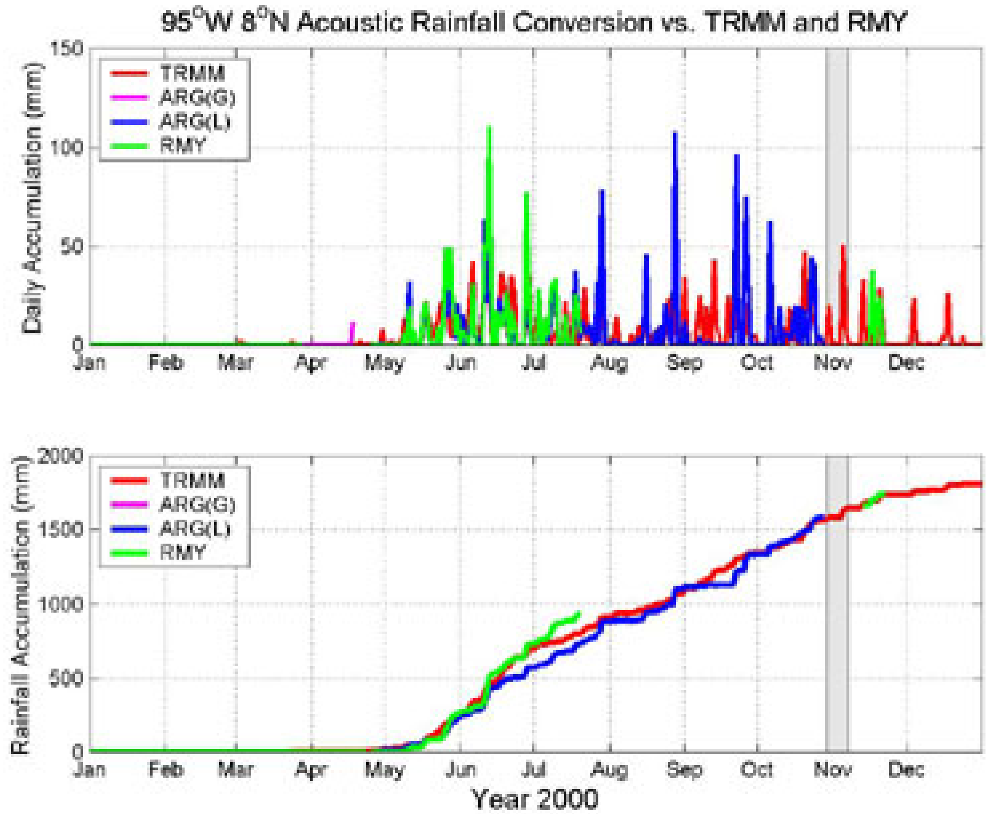

Figure 4. A comparison of rainfall accumulation from a TAO ocean surface mooring at 8°N, 95°W. The RMY rain gauge is mounted on the surface float. These surface instruments were stolen in July, a surprisingly big problem for remote ocean moorings. The TRMM satellite rainfall product (3B42) is a combined visible/infared estimate of rainfall and has a sampling strategy that is very different than the ARG or RMY data.

Using a comparison of 1-minute rainfall rate data from the R.M. Young rain gauges and the underwater sound field a new rainfall rate algorithm has been developed. The performance of this algorithm is shown in Figure 4. The figure shows some of the problems associated with rainfall measurements in oceanic regions. Agreement with the RMY rain gauge is excellent, until the RMY rain gauge is stolen in late July. The sub-surface location of the ARG allowed it to remain undetected by the vandals and continue to collect data. The comparison with TRMM satellite rainfall product (3B42) shows good seasonal agreement. The sampling strategy for the satellite rainfall product is very different temporally and spatially, and so only seasonal agreement should be expected as shown. At the end of the first deployment (Oct), the ARG cage started to rattle and no clear acoustic measurement were available. The mooring was replaces in November, however no new ARG was installed. Comparison of ARG measurements to the RMY rain gauges and the TRMM satellite product have similar stories.

IMPACT/APPLICATIONS

Analysis of the ambient sound field to provide important air-sea exchange measurements is a technology that should lead to important advances in our understanding of the physics of the air-sea interface. The measurement is simple, robust and covert. It can be made from small, autonomous drifters, or larger surface moorings. The measurements of wind, precipitation and bubbles are difficult to make by more conventional means, and are critical components of the air-sea fluxes of heat, water, momentum and gas that drive the interaction of the atmosphere and the ocean. These data are needed to develop and verify numerical models that analyze and forecast environmental (weather) conditions on small, regional and global scales. Through this effort we will be better able to interpret and monitor the underwater sound field. In addition to geophysical measurements of wind, rain and bubbles, the ARGs can be used to monitor biological activities and anthropogenic activities including shipping and active sonar activities.

TRANSITIONS

The Tactical Oceanography Warfare Support (TOWS) program at NRL has sponsored the development of air-deployable autonomous drifters (Selsor, 1993). Navoceano and NOAA are now deploying these sensors on a regular, but limited, basis (about 20 per year). The NOAA National Data Buoy Center is interested in "no-moving-parts" sensors for wind and precipitation. As part of the NOAA Pan-American Climate Studies (PACS) program, ARGs are to be mounted on some of the NOAA Tropical Atmosphere Ocean (TAO) array moorings. It is proposed that the acoustic sensors become a regular component of the NOAA TAO tropical ocean mooring array, and be regularly deployed as part of other large oceanic field experiments.

RELATED PROJECTS

"Acoustical Rainfall Analysis", sponsored by the Ocean Sciences Division, Physical Oceanography, of the National Science Foundation, broadly overlaps this project. The goal of this NSF project is to develop the acoustical inversion technology to provide a means of making oceanographic rainfall measurements. This project has funded the development of the new generation ARG and their deployment in the western tropical Pacific Ocean.

"Long-term Measurements of Air-Sea Processes: Rainfall, stratiform drizzle, ambient bubbles, and wind speed" is sponsored by the NOAA Pan-American Climate Studies (PACS) program. Its goal is to apply the acoustical weather analysis technology to obtain climatic rainfall data. This project uses the new ARG instruments, which are deployed on the Tropical Ocean Atmosphere (TAO) deep ocean mooring array in the eastern tropical Pacific Ocean as part of the Eastern Pacific Intercomparison of Climate (EPIC) program.

"Validation of Acoustical Rainfall Measurements" is sponsored by the NASA TRMM Program Office. This project focuses on the evaluation of different types of acoustical rainfall measurement algorithms. An emphasis on acoustical classification of rainfall type will use the comparison of weather radar data with the acoustical measurements.

REFERENCES

Farmer, D.M. and D.D. Lemon, 1984: The influence of bubbles on the ambient noise in the ocean at high wind speeds. *J. Phys. Oceanogr.* **14**, 1762-1778.

Lau, K.M., 1998: The South China Sea Monsoon Experiment (SCSMEX). *EOS* **78**, 599, 603.

Nystuen, J.A., 1996: Acoustical rainfall analysis: Rainfall drop size distribution using the nderwater sound field. *J.Acoust. Soc. Am.* **13**, 74-84.

Nystuen, J.A., 1997: Validation of Acoustic Measurements of Wind and Precipitation using Expendable Ambient Noise Sensor (ANS) Drifters, AN/WSQ-6 (XAN-2). Final Technical Report, Grant #N00014-94-1-G906, Naval Research Laboratory, via Defense Technical Information Center, Alexandria, VA 22304-6145, 21 p.

Nystuen, J.A., 1999: Relative Performance of Automatic Rain Gauges under Different Rainfall Conditions. *J. Atmos. and Oceanic Tech.*, **16**, 1025-1043.

Nystuen, J.A., 2001: Listening to Raindrops from Underwater: An Acoustic Disdrometer. *J. Atmos. and Oceanic Tech.* **18**, 1640-1657.

Nystuen, J.A., C.C. McGlothin and M.S. Cook, 1993: The underwater sound generated by heavy precipitation. *J. Acoust. Soc. Am.* **93**, 3169-3177.

Nystuen, J.A., M.J. McPhaden and H.P. Freitag, 2000: Surface Measurements of Precipitation from an Ocean Mooring: The Underwater Acoustic Log from the South China Sea", *J. Applied Meteor*. **39**, 2182-2197.

Nystuen, J.A. and H.D. Selsor, 1997: Weather Classification using Passive Acoustic Drifters. *J. Atmos. and Oceanic Tech.*, **14**, 656-666.

Selsor, H.D., 1993: Data from the sea: Navy Drifting Buoy Program. *Sea Technology* **34**, 53-58.

Serra, Y, P.A. Hearn, H.P. Freitag and M.J. McPhaden, 2001: ATLAS self-siphoning rain gauge error estimates. *J.Atmos.and Oceanic Tech.***18**, 1989-2002.

Vagle, S., W.G. Large and D.M. Farmer, 1990: An evaluation of the WOTAN technique for inferring oceanic wind from underwater sound. *J. Atmos. and Ocean. Tech.* **7**, 576-595.

Zedel, L., L. Gordon and S. Osterhus, 1999: Ocean Ambient Sound Instrumentation System (OASIS): Acoustic Estimation of Wind Speed and Direction from a Sub- surface Package. *J. Atmos. Oceanic Tech.* **16**, 1118-1126.

PUBLICATIONS

Nystuen, J.A., 1997: Validation of Acoustic Measurements of Wind and Precipitation using Expendable Ambient Noise Sensor (ANS) Drifters, AN/WSQ-6 (XAN-2). Final Technical Report, Grant #N00014-94-1-G906, Naval Research Laboratory, via Defense Technical Information Center, Alexandria, VA 22304-6145, 21 p.

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Nystuen, J.A., 1999: Relative Performance of Automatic Rain Gauges under Different Rainfall Conditions. *J. Atmos. and Oceanic Tech*., **16**, 1025-1043.

Nystuen, J.A., 1999: Listening to Raindrops, *Solstice* **10**, Number 2, http://www.csfnet.org/image/solstice/win99/janystuen/listen.html

Nystuen, J.A., M.J. McPhaden and H.P. Freitag, 2000: Surface Measurements of Precipitation from an Ocean Mooring: The Underwater Acoustic Log from the South China Sea", *J. Applied Meteor*. **39**, 2182-2197.

Nystuen, J.A., 2001: Listening to Raindrops from Underwater: An Acoustic Disdrometer. *J. Atmos. and Oceanic Tech.* **18**, 1640-1657.

Nystuen, J.A. and E. Amitai, 2002: Temporal Resolution of Extreme Rainfall Rate Variability and the Acoustic Classification of Rainfall", *J. Geophys. Res.*, accepted.